VISA II Experiment at ATF

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Collaboration

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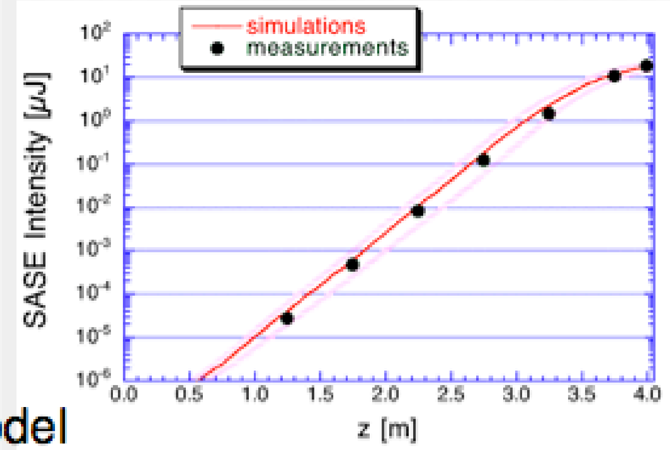
  - M. Ferrario, L. Palumbo, C. Vicario
- POSTECH, Korea
  - J. Huang

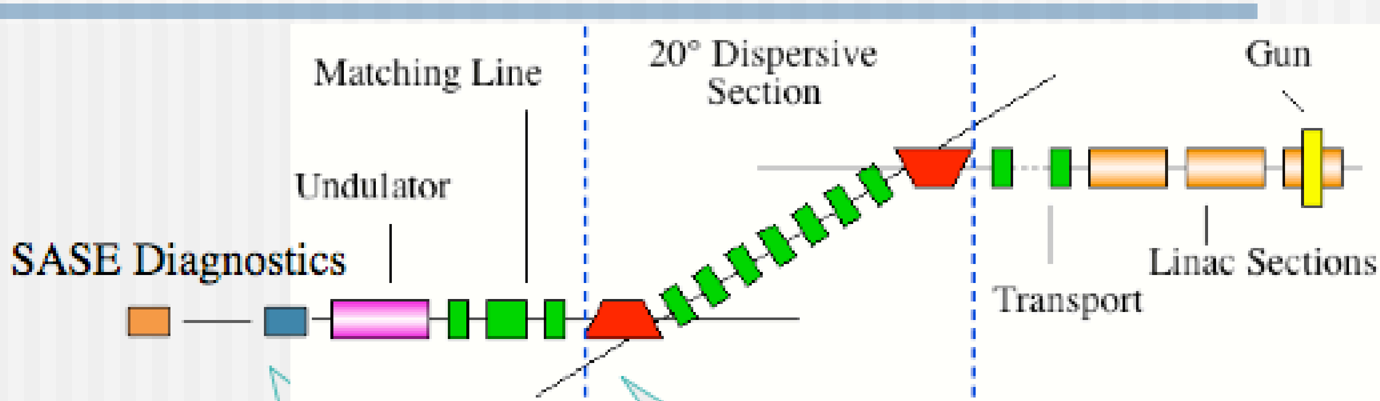
VISA I Summary

VISA-I (1999-2001)

- ATF (Accelerator Test Facility at BNL) S-band photoinjector ($\mathcal{E} \sim 71$ MeV, $\varepsilon_n \sim 2\ \mu$m, $Q \sim 300$ pC)
- Strong focusing 4-m undulator (K=1.26, $\beta_{x,y} \sim 30$ cm)
- Very short gain length $L_G \sim 18$ cm
- Saturation at $\lambda \sim 840$ nm
- Peak power $P \sim 60$ MW
- Good agreement with numeric model



VISA I Summary

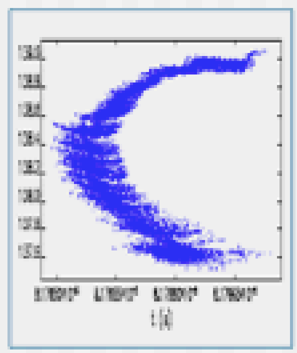


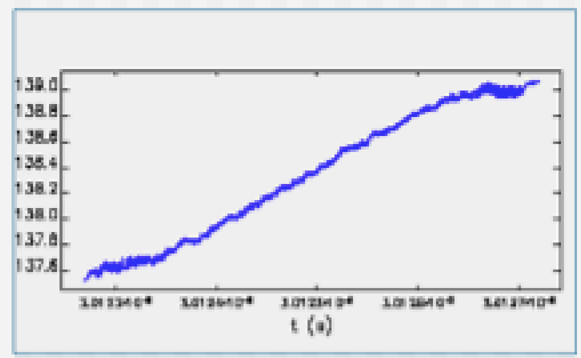
$L_G \sim 17.9$ cm
$\Delta\omega/\omega \sim 1.2$ % (single spike)

$I_p \sim 250$ Amp
$\Delta p/p \sim 0.14\text{-}0.20$ %

$I_p \sim 55$ Amp
$\Delta p/p < 0.05$ % (uncorrelated)

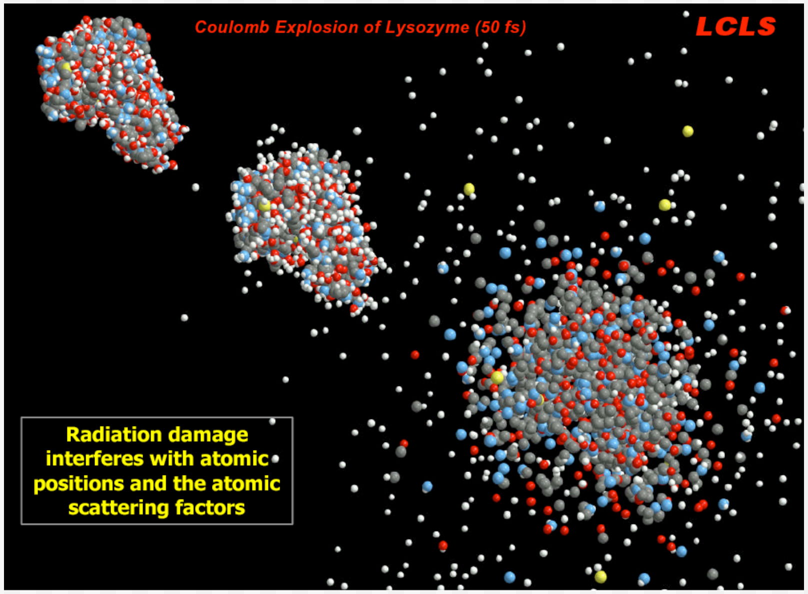
$$T_{566} = \frac{\partial R_{56}}{\partial(\delta p/p)} \approx -7 \ \mathrm{m/rad^2}$$

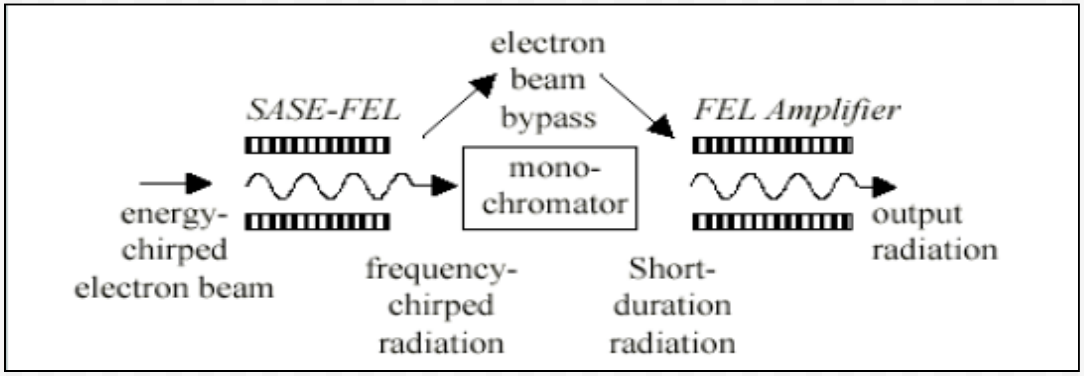




VISA II: Motivation

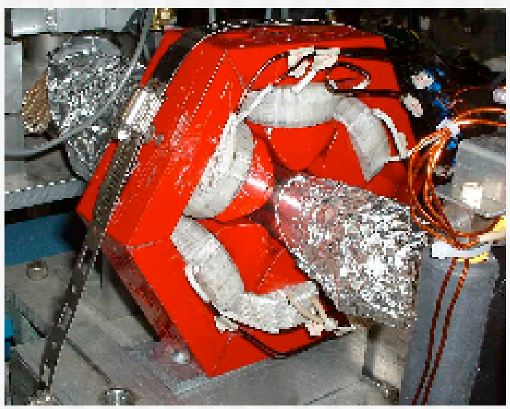
- Proposed Scheme for ultra short pulses
  - Energy chirped e-beam ➔FEL➔ freq. chirped radiation
- Explore Limits of SASE FEL with energy chirped e-beam
- Develop advanced beam manipulation & measurements

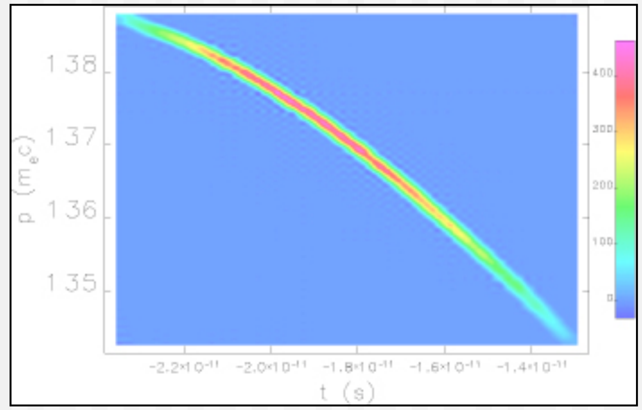




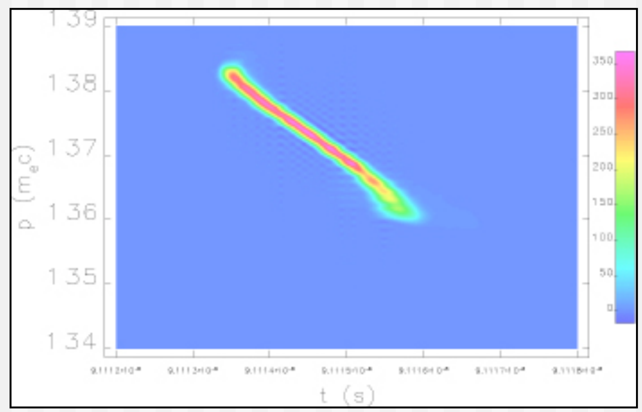
VISA II

- ✓ Energy chirp SASE FEL operation
  - linearize F-line
- ✓ Running Conditions
  - Back of crest acceleration
  - Negative R56 compression
  - 70% Transmission
- ✓ Start-to-end Simulations
  - Frequency chirped radiation
- ✓ Modified FROG



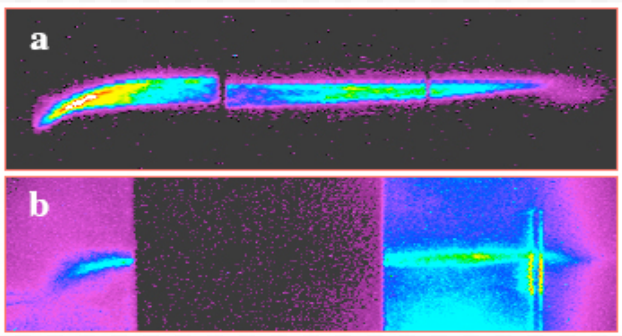


Longitudinal Phase Space for VISA II Case post linac (above) and pre-undulator (below).



VISA IB: Unusual Spectrum

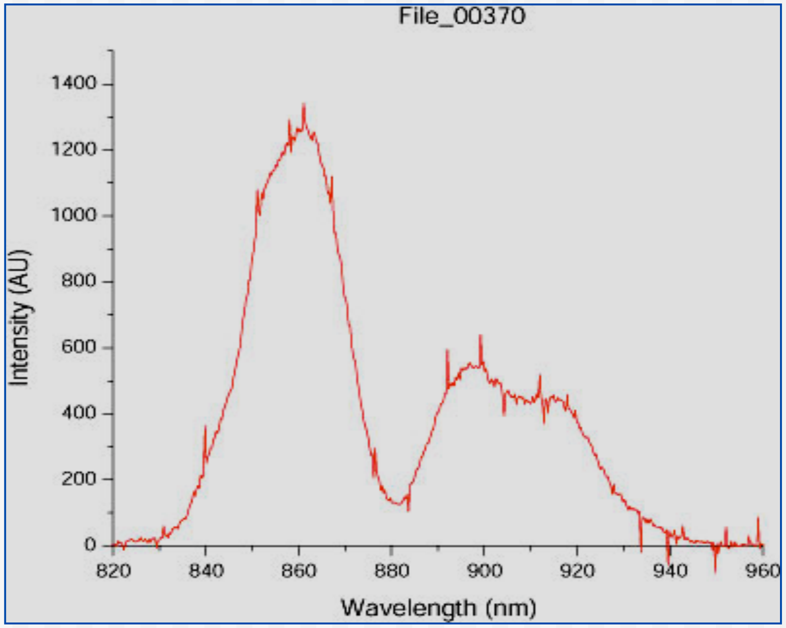
- ✓ Close to saturation (~2 μJ)
- ✓ Strongly chirped beam
- ✓ Over 10% bandwidth observed
- ✓ Very reproducible and unusually stable



e-beam at HES

a) fully closed slits (500 pC, 2.8% chirp)

b) fully open slits (60 % Transmission, 330pC)



FEL Spectrum at VISA measured with Ocean Optics USB2000 Spectrometer.

Where did the bandwidth came from?

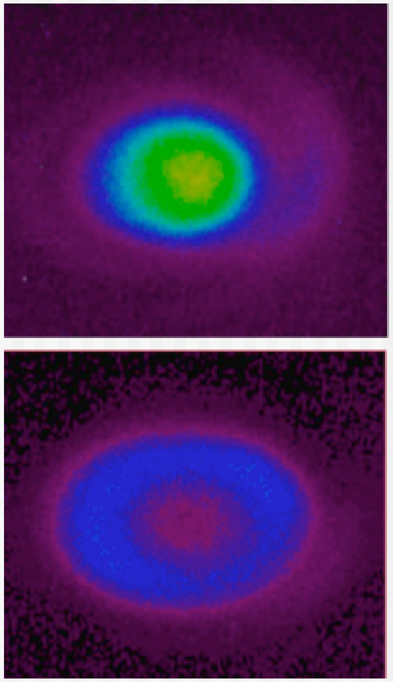
Expected FEL bandwidth is much smaller:

$$\tilde{\rho} = \frac{\lambda_U}{4\pi\sqrt{3}L_G} \le .0045 \qquad \left(\frac{\Delta\omega}{\omega}\right)_{FEL} \le 4\tilde{\rho} \approx 2\ \%$$

Energy spread effect? $$\left(\frac{\Delta\omega}{\omega}\right)_{\gamma} \sim 2\frac{\Delta\gamma}{\gamma} \le 2\ \%$$

Short pulse effect? $$\left(\frac{\Delta\omega}{\omega}\right)_{FT} \sim \frac{\lambda_R}{\lambda_C} \sim 4\ \%$$

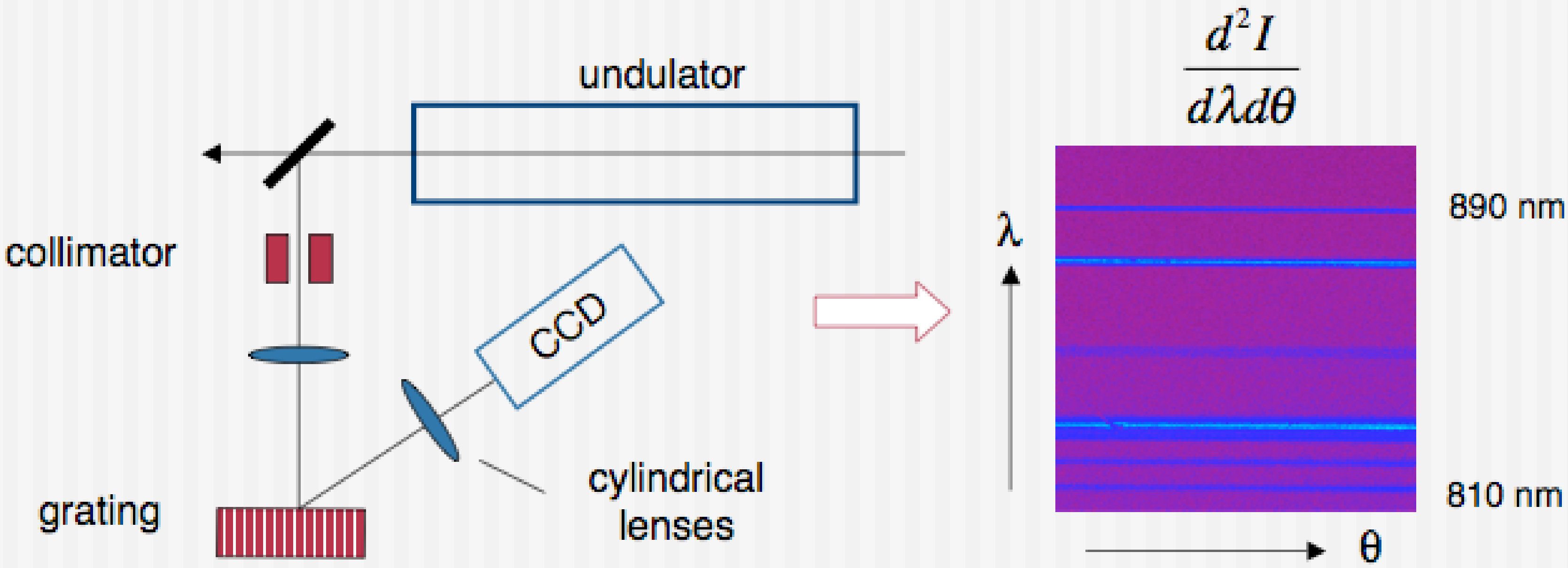
Large emission angles? $$\left(\frac{\Delta\omega}{\omega}\right)_{\theta} = \frac{(\gamma\theta)^2}{1+K^2/2}$$



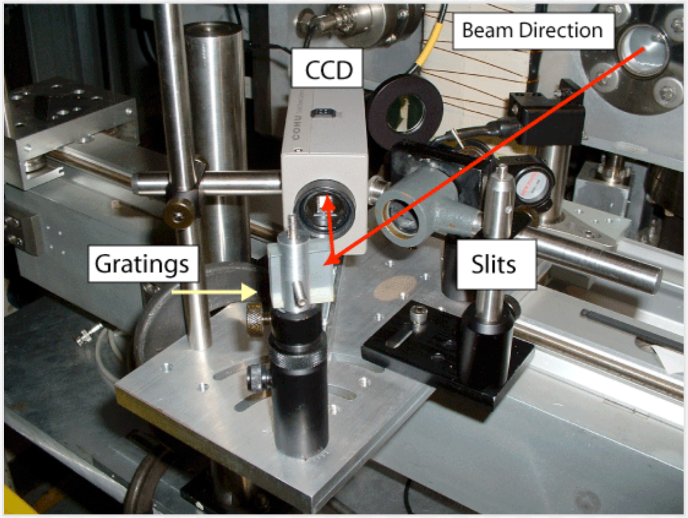
up to 2.5 mrad

Double Differential Spectrum

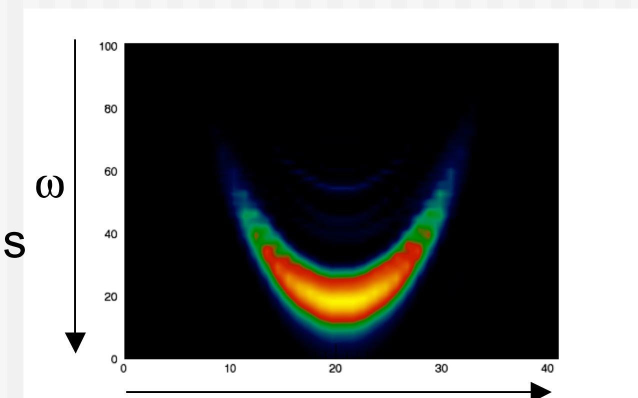
- One can measure directly double-differential spectrum, and observe correlation between the spectrum and longitudinal distribution:



Double Differential Spectrum

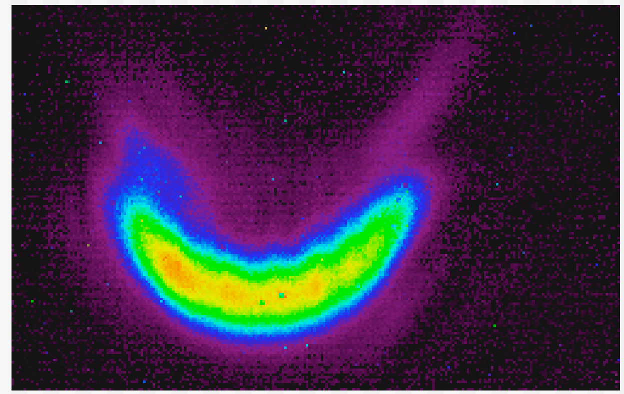


Genesis

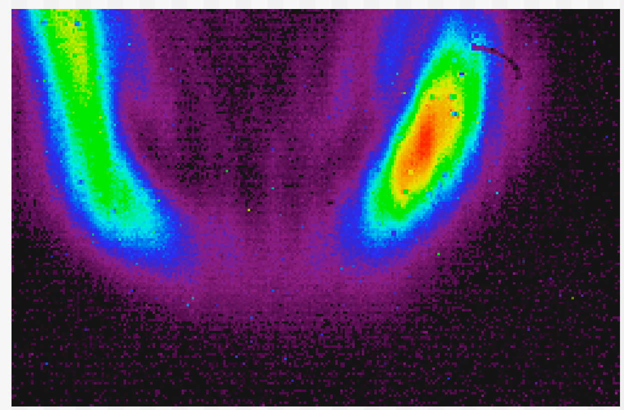


θ

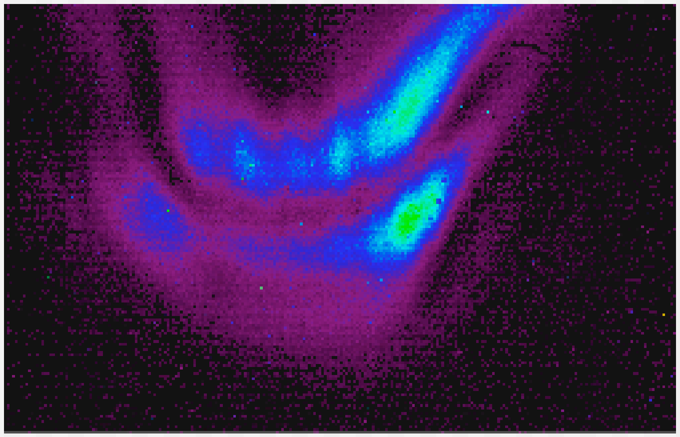
normal gain



high bandwidth gain

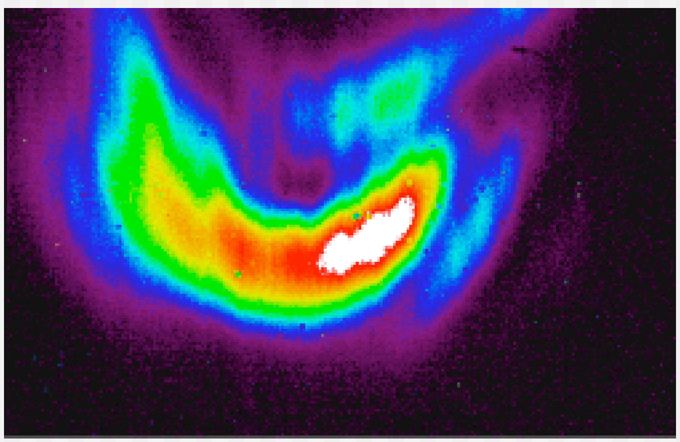


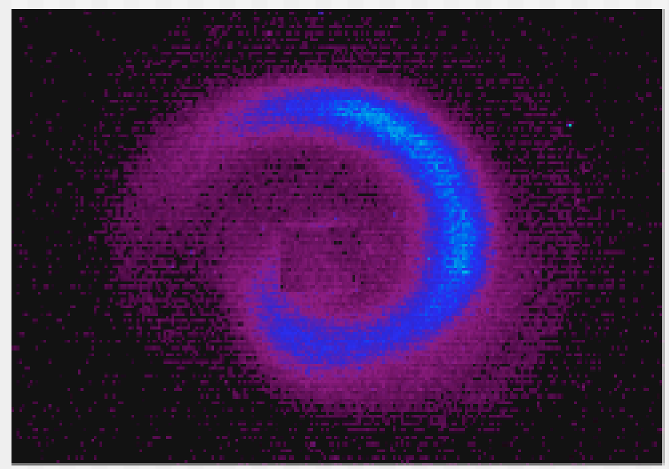
Double Differential Spectrum



multiple modes

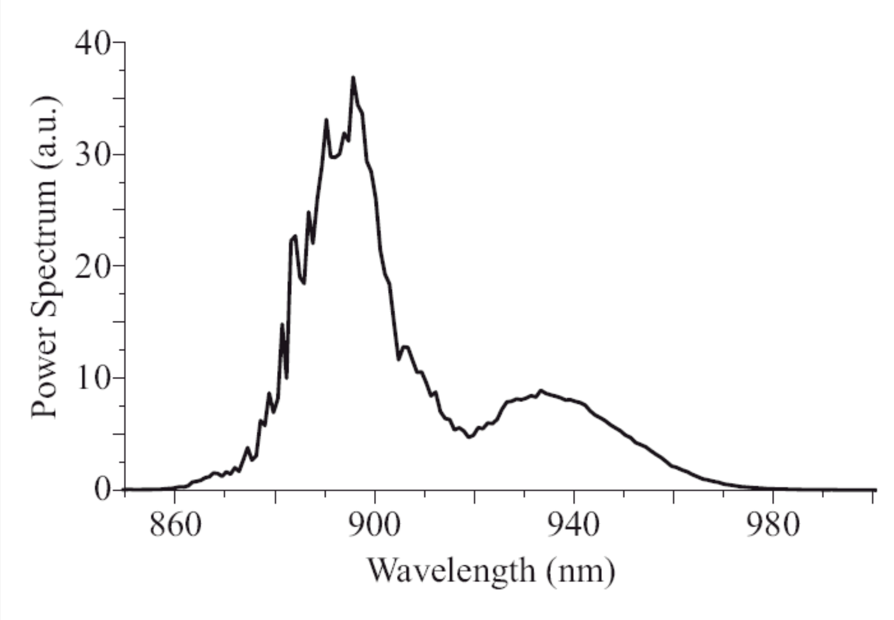
multiple modes asymmetric





VISA IB: Analysis

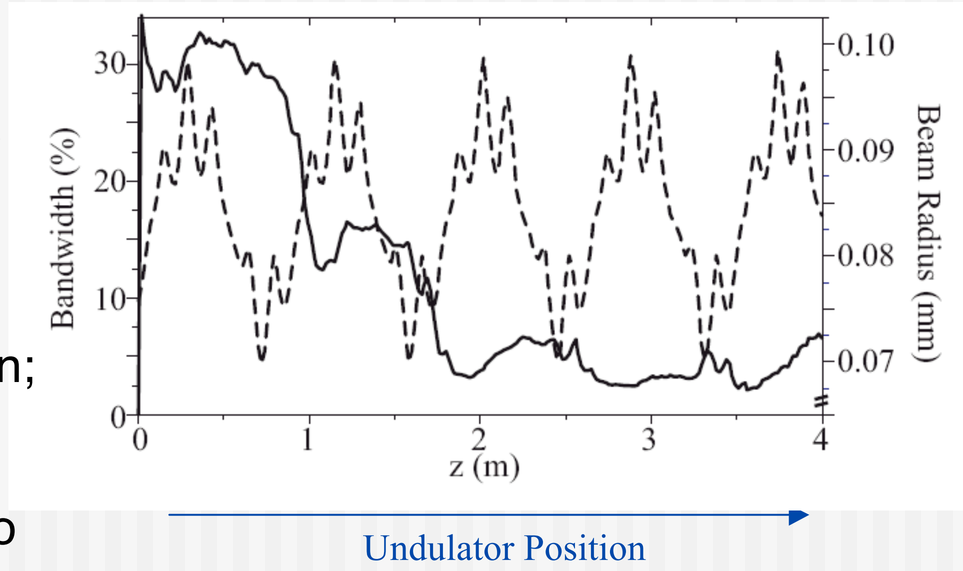
- ✓ Start-to-End
  - Experimental Spectrum features reproduced
  - Numerical Studies on no energy spread yield similar results
  - The condition was first observed when beam was lunched off-axis by 300 μm



FEL output Spectrum reproduced by Genesis (~10% bandwidth)

VISA IB: Analysis

- ✓ Bandwidth evolution depends on transverse dynamics in the beam
- ✓ Oscillations can be due to:
  - uncompensated dispersion;
  - focusing mismatch;
  - off-axis beam injection into the undulator;



G. Andonian *et al.*, Phys. Rev. Lett. **95**, 054801 (2005)

Why weren't we able to match the beam?

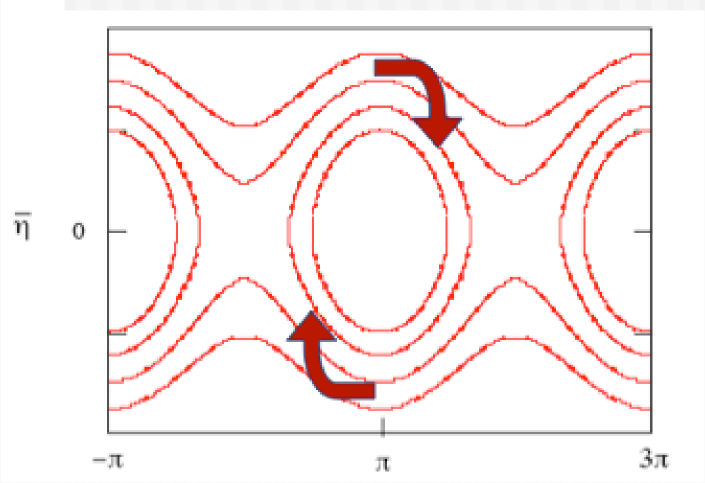
Why VISA-1 had normal bandwidth?

Disclaimer: material below this line is a personal opinion of the speaker, and does not reflect the official position of VISA collaboration.

Is it possible that the FEL performance improves, when the beam is mismatched?

Yes, when the mismatch is called "beam conditioning".

A. Sessler, D. Whittum, L. Yu, Phys. Rev. Lett. 68 (1992)



Artificially introduced phase space correlation which reduces relative slippage in the beam

$$\frac{\delta\gamma}{\gamma_0} = \frac{\varepsilon_N}{4\gamma_0\beta}\frac{\lambda_u}{\lambda_r}r^2$$

In the conditioned beam the emittance and energy spread effects cancel each other out, effectively increasing the number of particles trapped inside the resonant separatrix.

Hypothesis #1 ("beam self-conditioning"): when a matched electron beam has a random phase space correlation, it can be partially conditioned by mismatching.

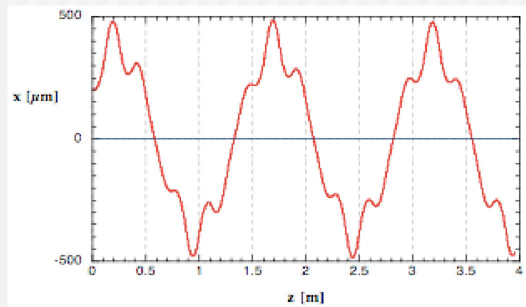
VISA-1B is a fine example of randomly correlated beam

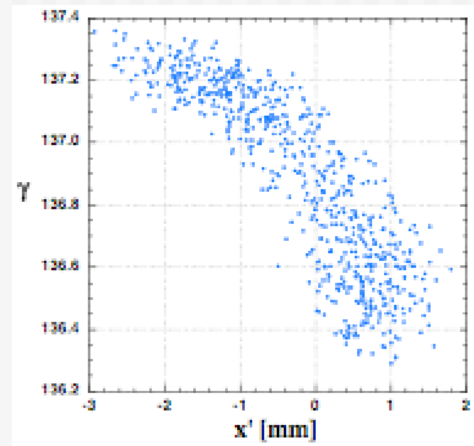
The motion is not a simple sinusoidal, so the slippage needs to be evaluated numerically:

$$\boxed{\left\langle \frac{dS_\beta}{dz} \right\rangle = -\frac{r^2}{4\tilde{\beta}^2} \qquad \tilde{\beta} \approx 0.21\ \mathrm{m}}$$

$$r^2 = r_x^{\,2} + r_y^{\,2}$$

$$r^2 \approx 6.0x^2 + 0.090x'^2 + 1.25xx'$$





from ELEGANT

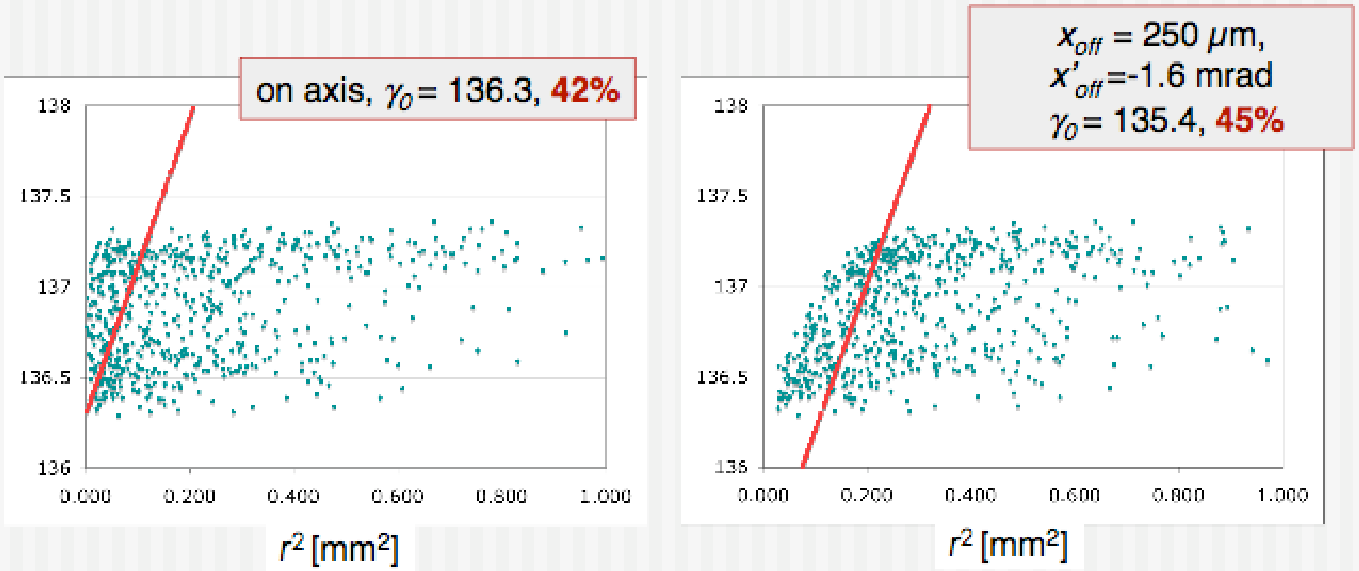
Energy spread induced slippage is straight forward:

$$\boxed{\left\langle \frac{dS_\gamma}{dz} \right\rangle = \frac{\lambda_r}{\lambda_u}\left[1 - \frac{\gamma_0^{\,2}}{(\gamma_0 + \delta\gamma)^2}\right] = 2\frac{\lambda_r}{\lambda_u}\frac{\delta\gamma}{\gamma_0}}$$

$$\left\langle \frac{dS_\gamma}{dz} \right\rangle + \left\langle \frac{dS_\beta}{dz} \right\rangle = 0 \quad \Rightarrow \quad \boxed{\frac{\delta\gamma}{\gamma_0} = \frac{\lambda_u}{8\tilde{\beta}^2\lambda_r} r^2}$$

One can inject the beam off-axis into the undulator and numerically find *x* and *x'*, which would minimize the average relative slippage in the beam: x_{off} = 250 μm x'_{off} = -1.6 mrad

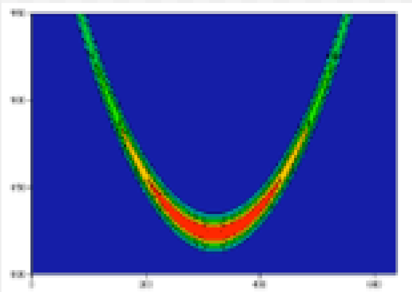
Hypothesis #2: the FEL performance improves when the beam phase space distribution is closer to the conditioned beam.



(Gain-guided operator will eventually find such operating condition.)

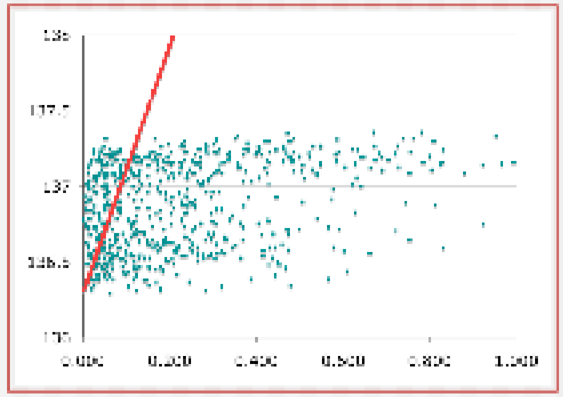
Hypothesis #3: the microbunching wavelength for any beam is given by standard resonant condition, $\lambda_b = \frac{\lambda_u}{2\gamma_0}\left(1+\frac{K^2}{2}\right)$, but γ_0 is defined by the beam conditioning curve; therefore, λ_b is always red-shifted.

“Normal” lasing mode

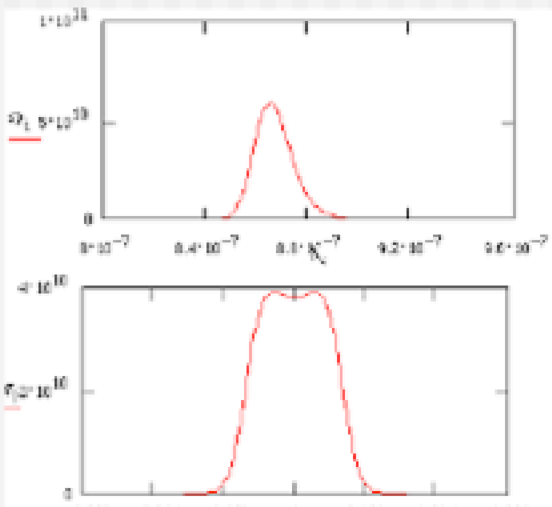


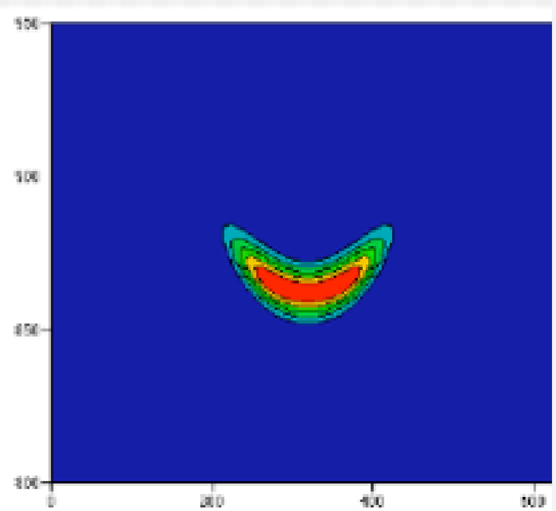
Spontaneous emission DDS

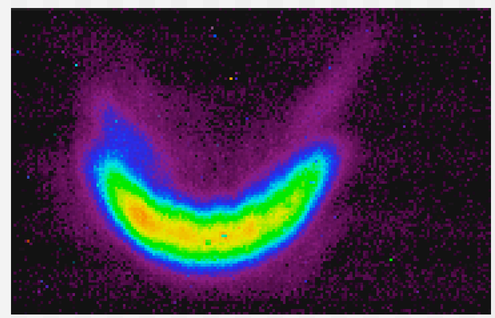
$<\gamma> = 136.9,\ \gamma_0 = 136.3$



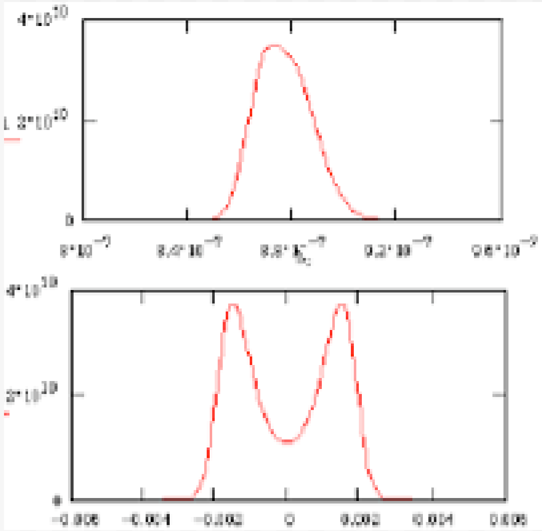
cut at microbunching wavelength

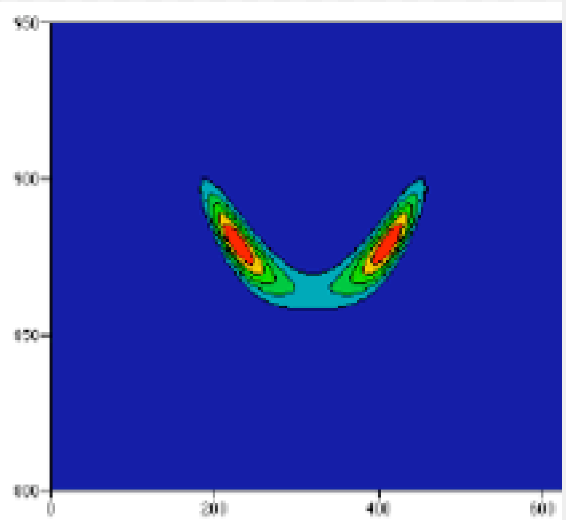




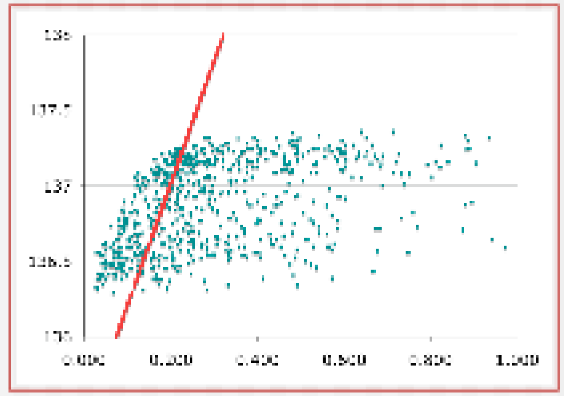


“Conditioned” mode

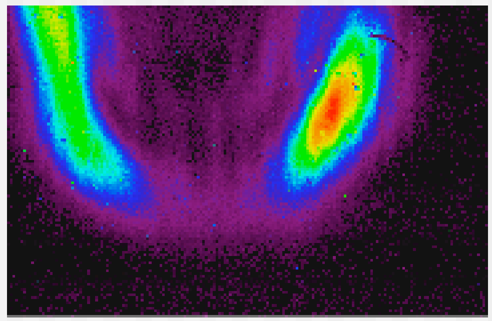




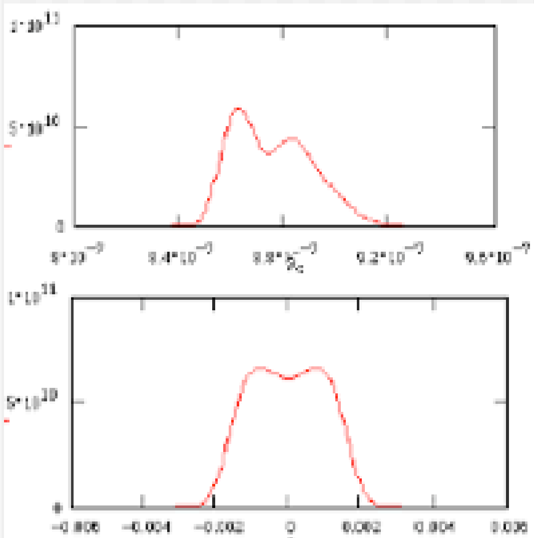
$\langle\gamma\rangle = 136.9,\ \gamma_0 = 135.4$

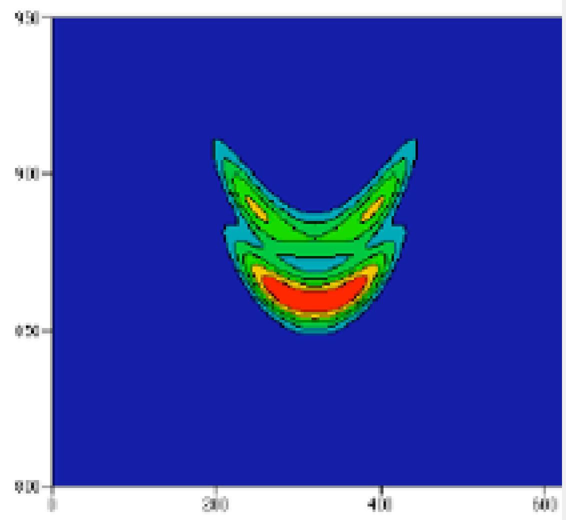


- Hollow angular distribution
- Larger gain
- Asymmetric e-beam, off-axis, with poor horizontal matching
- Red-shifted spectrum



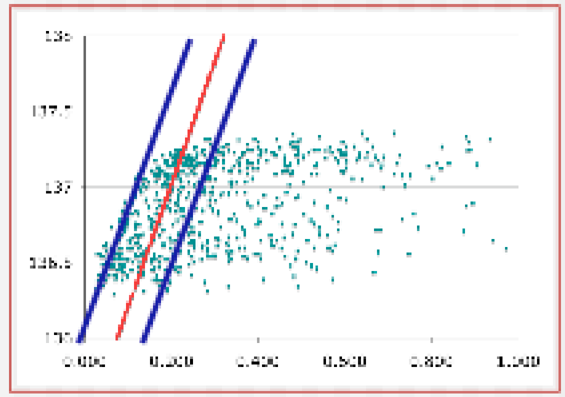
High-bandwidth mode



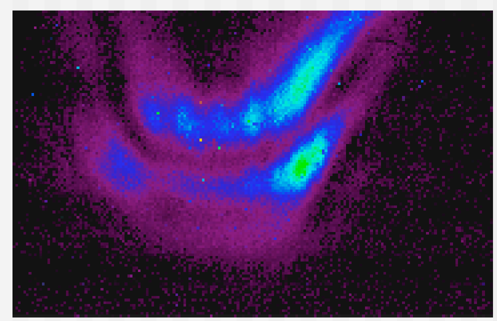


$\langle\gamma\rangle = 136.9$

$\gamma_1 = 136.1,\ \gamma_2 = 135.9$

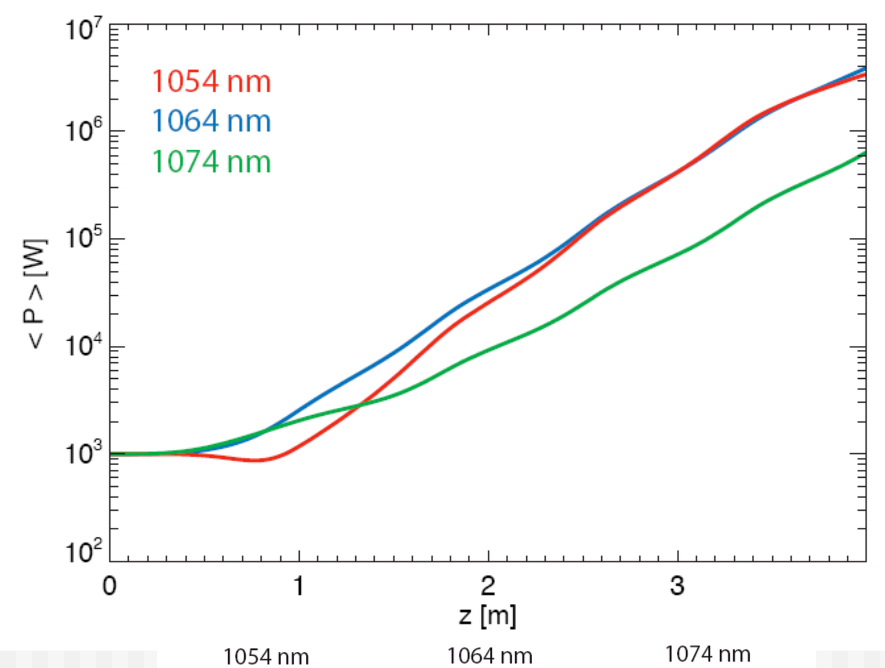


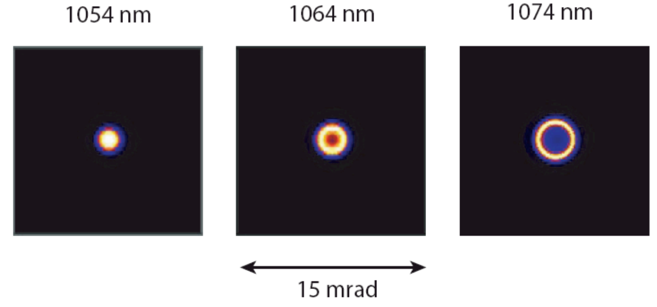
- 2-3 modes with different "zero"-energy can coexist
- Wide red-shifted spectrum
- Mode interference can generate exotic far-field angular distribution



Future plans: Seeded Amplifier

- ✓ Far-field studies
  - Deliver high power without damaging optics
  - Increase angle, decrease intensity
  - Need short gain length to obtain short Rayleigh range
- ✓ Use VISA undulator
  - 61 MeV beam
  - Seed with 1064 nm YAG
- ✓ Alignment Issues
  - Delay line
- ✓ Study detuning with Start-to-end Sims





Conclusions

- ✓ VISA IB
  - Observed ultra wide bandwidth
  - Demonstrated high gain chirped beam amplification
  - Can lead to further studies on hollow modes
  - Show confidence in start-to-end suite
- ✓ Seeded amplifier runs & data forthcoming